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14. ABSTRACT

Terminal guidance of weapons immediately prior to impact is a demanding control problem. While Global Positioning System (GPS) guidance can get a weapon close to a target, a greater level of accuracy is often needed to account for such uncontrollable factors as the movement of a target. The inclusion of an alternate terminal guidance ability therefore will increase the chances of the missile reaching its target. This final report details results of a Small Business Innovation Research (SBIR) Phase I project to develop a novel, extremely high speed image-recognition control system that seamlessly links an image sensor input, target identification and clutter discrimination processes, and control outputs. The missile guidance architecture evaluated in this project is based on a novel mathematical methodology that eliminates many faults or limits found in existing control architectures. Mathematical modeling of the system demonstrate that it can track both simple and complex images on backgrounds that range from plain to fairly cluttered. Additional refinements are needed to improve the system's ability to discriminate between target and decoy images.

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HIGH-SPEED IMAGE RECOGNITION CONTROL SYSTEM

Contract No. N68335-01-C-0002

SBIR Topic #N00-011, "Integrated Missile Seeker Signal-Processor Development and Implementation"

Final Report

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HIGH-SPEED IMAGE RECOGNITION CONTROL SYSTEM

FINAL REPORT

Introduction

Terminal guidance of weapons immediately prior to impact is a demanding control problem. While Global Positioning System (GPS) guidance can get a weapon close to a target, a greater level of accuracy is often needed to account for such uncontrollable factors as the movement of a target. GPS signals can also be jammed, or the GPS receiver may be damaged as it approaches a defended area. The inclusion of an alternate terminal guidance ability therefore will increase the chances of the missile reaching its target.

A guidance system suitable for missiles must be fast, inexpensive, and capable of accurately recognizing a target under varying conditions including ambient weather and changing aspect ratio and range, and in the presence of clutter or countermeasures. Real-time translation of the image data into control signals for the weapon is also required.

In this Small Business Innovation Research (SBIR) Phase I project, QEI Technologies, Inc. endeavored to develop a novel, extremely high speed image-recognition control system that will seamlessly link an image sensor input, target identification and clutter discrimination processes, and control outputs. The missile guidance architecture evaluated in this project uses a novel mathematical methodology whose hardware realization was designed to result in an extremely fast, novel, and inexpensive pattern recognition and control system.

The guidance system compares input "symbols" (data in symbolic format from an imaging sensor) to a set of symbols stored in matrix form. As the input image changes (due to relative motion between the image and weapon), a set of continuous resonant feedback patterns is set up between the input image and the stored target images. Output from this resonance feedback is fed into a final resonant loop for generation of the control pattern to guide the weapon. The block diagram in Figure 1 illustrates the operation of the control system.

As can be seen in the figure, no microprocessor or other digital processing is required. The system instead operates by matching the set of input "symbols" – i.e., data in symbolic format from an imaging seeker – to a stored set in a second matrix. This concept can be visualized as storing a holographic image in digital matrix form and generating a pattern of the input image on some projection of the stored matrix via the generation of resonant patterns. As the input image changes (due to relative motion between the target and weapon), a continuous resonant feedback is set up in the first loop between the input image and stored "holographic" image matrices. This loop will result in mapping to a set of symbols that is fed into the second resonant loop for generation of a control pattern to guide the weapon.

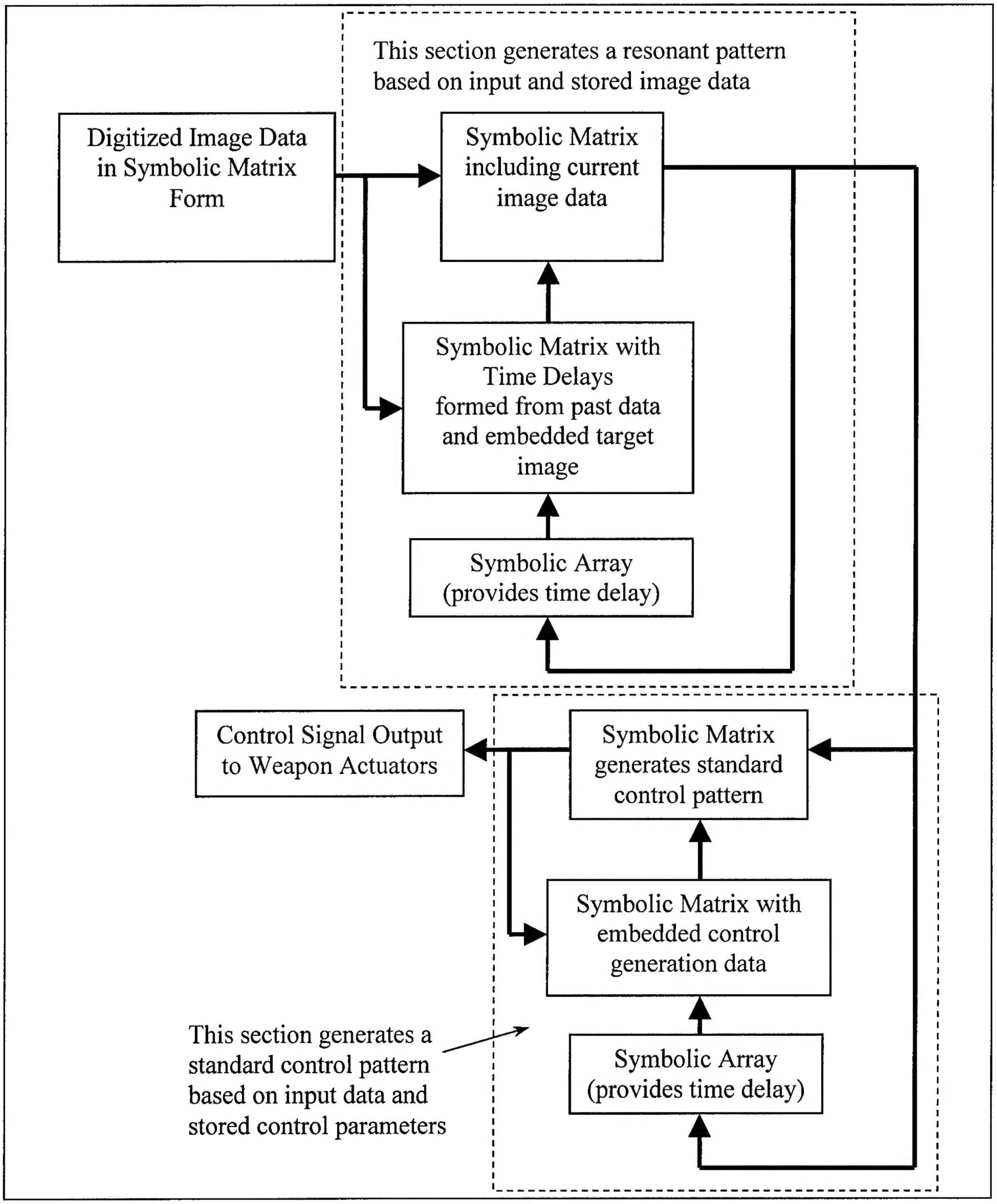


Figure 1. Symbolic Control System

The overall objective of this three-phase program is to develop a high-speed image-recognition control system for terminal guidance of a variety of weapons. In Phase I, the effort focused on mathematically modeling the proposed control system as coupled to an imaging sensor. This report describes the results of the Phase I effort, including information on the following topics:

- Phase I Technical Objectives,
- Work Plan,
- Results by task
- Recommendations and Conclusions

Technical Objectives

Phase I technical objectives are listed below:

- Mathematically model the imaging seeker data output, control matrices, and output matrices including semiconductor component delay times
- Test the control system response to a variety of input conditions, including rapidly changing scenarios and targets in clutter
- Generate a Bill of Materials for producing a hardware implementation of this control system using off-the-shelf components

Completion of these technical objectives allowed the following questions to be answered, thereby enabling a determination of feasibility to be made:

- Does the proposed control system appropriately recognize targets, including in cluttered conditions?
- Does the system generate appropriate outputs to track and pursue targets?
- Are there any conditions that can cause the control system to lock up or otherwise stop following a target?

Phase I Work Plan

The Phase I work plan is divided into four technical tasks. These tasks, together with their associated objectives, are listed below.

Task 1. Mathematically Model Symbolic Control System Coupled to an Imaging Seeker

The objective of this task is to mathematically model the symbolic control system including simulated image inputs.

A model for the entire control system was developed using MathCAD software using symbolic notation. The model is based on simpler but proven models of this control system that the PI has used in the past (Sullivan 1999). The model's configuration is illustrated in Figure 2 and described below.

The model consists of the following elements:

Light Detection Array. The array is fed predetermined test patterns, and the array generates a simulated pixel-by-pixel response to the test pattern. Each pixel of the array (256 x 256 pixels for simulations) is directly coupled to an analog to discrete symbolic converter. Each converter possesses 256 discrete output lines (corresponding to an 8-bit level of image resolution), and only one output line is selected based on the value of the analog input. This serves to simulate the fastest responses the control system may achieve, and serves as an accurate representation of the data flow to be used in Phase III systems.

Image Recognition Matrices. A set of mapped matrices with built-in time delays are created to perform the pattern matching and to store specific patterns to be recognized. The patterns are stored in a manner analogous to a holographic approach, so it is not necessary to store an exact pattern for every aspect ratio of a target.

Control Matrices. A second set of mapped matrices with built-in time delays convert the recognized pattern (as output by the image recognition matrices) into a standard control pattern whose shape and position provides control to the missile.

Output Conversion. The standard control pattern is converted into a single aiming point on a matrix-based output grid.

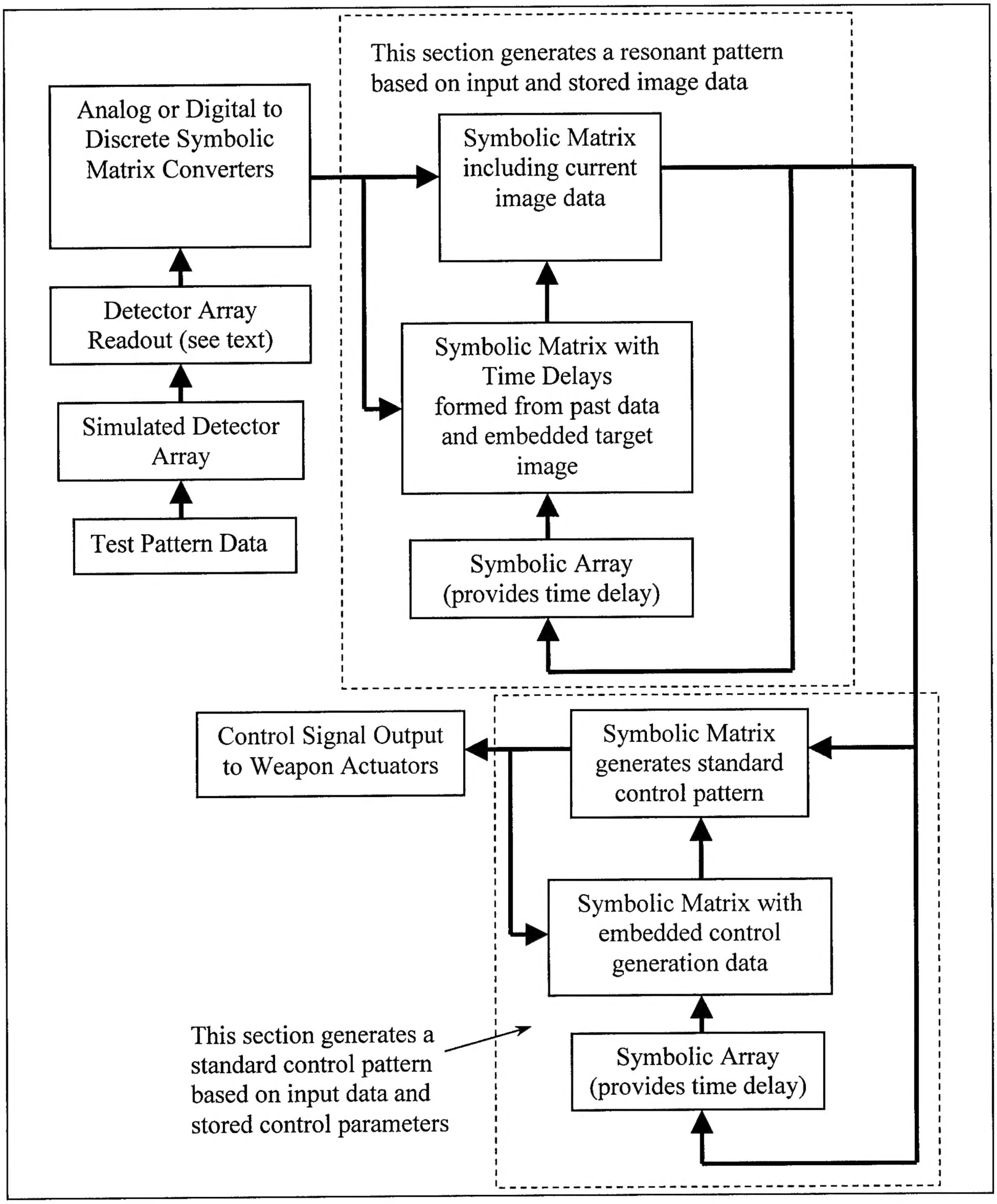


Figure 2. Symbolic Control System as Modeled

Task 2. Conduct Simulations of the Symbolic Control System.

The objective of this task is to conduct mathematical simulations of the symbolic control system performance using the model developed in Task 1.

The model developed in Task 1 is used to simulate the behavior of the control system as it is presented with a variety of input scenarios. Various shapes were superimposed on backgrounds containing various sorts of clutter. Specific tests include the following:

Basic Pattern Recognition. The system must first be evaluated in terms of how well and how quickly it recognizes basic shapes in a clutter-free environment. The shape size and orientation are varied during these tests.

Multiple Patterns. The system is presented with multiple patterns in the same image and evaluated in terms of its ability to select the appropriate one to pursue.

Noise and Clutter. The effect of noise and clutter on individual pattern recognition will be evaluated using both random and patterned backgrounds.

Figure 3 is a pictorial representation of how simulation data enter the model system, generate resonant patterns, and output control signals.

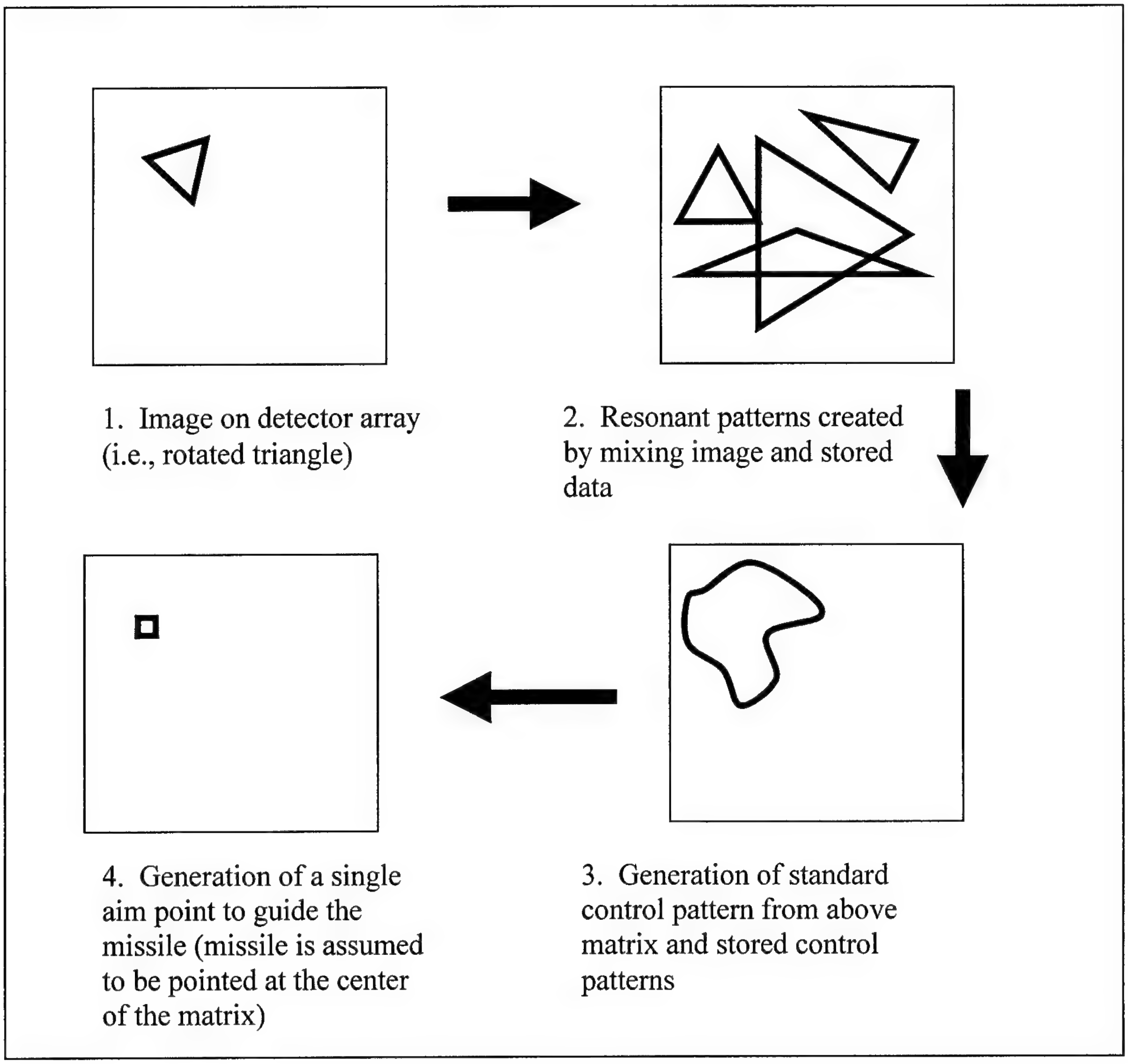


Figure 3. Pictorial Representation of Data Processing in the Symbolic Control System.

Task 3. Hardware Analysis.

The objective of this task is to begin selecting appropriate components that can be used to implement the control system.

This begins the process of identifying suitable parts with which to build the control system. Results from this search will allow predictions to be made of near-term and long-term anticipated control system performance.

Task 4. Perform Technical and Economic Evaluation.

The objective of this task is to complete an initial evaluation of the Phase I results to assess feasibility and potential for follow-on development.

This task includes a preliminary technical and economic evaluation of the Phase I results. This evaluation includes comparing the modeled performance and characteristics of the control system against military requirements and available electronic hardware. Cost estimates are also developed for production control systems.

Results

Task 1. Mathematically Model Symbolic Control System Coupled to an Imaging Seeker

A model for the entire control system has been developed using MathCAD software. This system consists of the following major elements:

- A program for generating embedded pattern targeting information
- A program that generates the test images (input program)
- The program that performs the actual pattern recognition task

The input program accepts standard bitmap images for use by the pattern recognition program. The pattern recognition program compares the input matrix to the embedded image matrix and generates an output matrix that includes a correlation quality figure indicating the quality of fit between the input image and each of the stored target images. The image recognition program's output matrix generates simulated control signals to guide the missile to the desired aim point on the image.

Because of software limitations, the Phase I targeting system is divided into two subsets, each using a different type of embedded pattern and mapping to different paths upon past/present image comparison. The first subset is for moving targets and assumes the background changes measurably less than the target and any decoy. The second subset is for fixed targets, where the target image, decoys, and background are considered a semi-fixed entity.

The two subsets use mapping to past/present comparisons and null responses that are mirrored to each other. Incorporating both into a single system results in the degradation of both. In a physical system, both subsets would be operating in parallel and generate independent targeting information. The one subset whose correlation to the embedded target is highest provides the primary targeting point. This approach allows operation against a target that can both move and then remain motionless. The first half of each subset is identical and can use the same video processing substrate.

Task 2. Conduct Simulations of the Symbolic Control System

The model developed in Task 1 has been used to simulate the behavior of the control system as it is presented with a variety of input scenarios. Several simulations were run, including the one described below and in Figure 4.

The target in this simulation is a grainy image of a Humvee that is moving relative to the field of view (a stationary object such as a building would also appear to be moving from the viewpoint of a missile). The background in this simulation is slightly cluttered and variable. The purpose of this simulation was to evaluate the system's ability to distinguish a grainy and somewhat complex image from simple but similarly shaped objects such as rectangles and circles. In addition, the system's ability to track the image against a varying background was evaluated by adjusting the background from frame to frame.

Figure 4 illustrates how the system tracks the target image by showing three things: 1) the input image, 2) the output of the image recognition program, and 3) the aim point. The output of the image recognition program shows "hits" in the form of dots – what is not clearly illustrated in this figure is that each dot represents a correlation quality figure indicating the quality of fit between the input image and each of the stored target images. This quality of fit plays a significant role in determining the aim point, although in Phase I the algorithm for determining the aim point is fairly crude. Nonetheless, Figure 4 clearly illustrates an accurate aim point for this simulation. With the exception of the last frame, the program successfully tracked the target.

A second simulation illustrates the case of a stationary target (Humvee) with moving background images. One of the moving images, a triangle consisting of lots of small squares of various shades, was used to evaluate the model's ability to distinguish between the target image and a dissimilar image containing a large number of edges.

Figure 5 shows the results of this simulation. In this case, the moving triangle received a more hits than the target Humvee, indicating that the system was distracted by the large number of edges in the moving triangle. Modifying the system to track a stationary target moves the aim point to the Humvee. However, if the Humvee and triangle had the same motion relative to one another, the system would have trouble distinguishing between them.

Figure 4. Simulation of Symbolic Control System Using Humvee Target

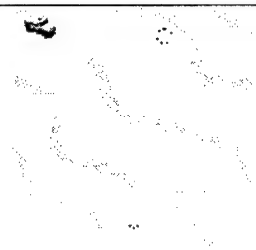
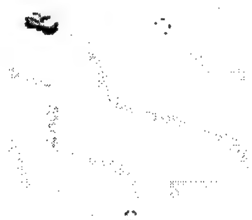
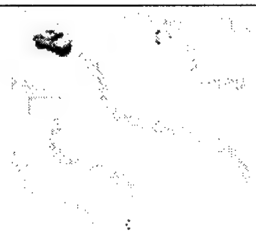
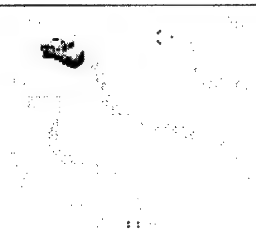
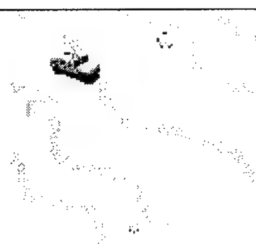
	Input Image	Output of Image Recognition Program	Aimpoint
Frame 1			
Frame 3			
Frame 5			
Frame 7			
Frame 9			

Figure 4, cont'd

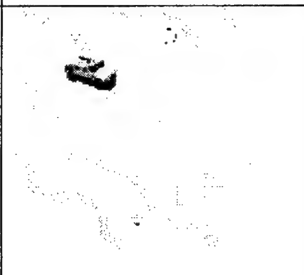
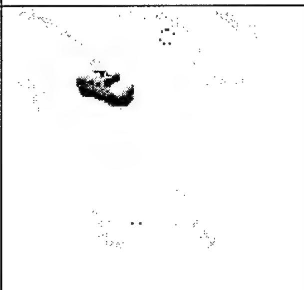
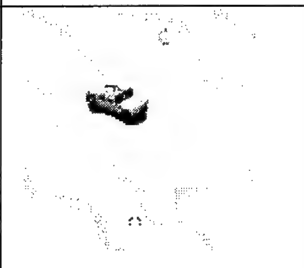
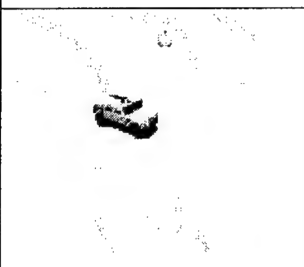
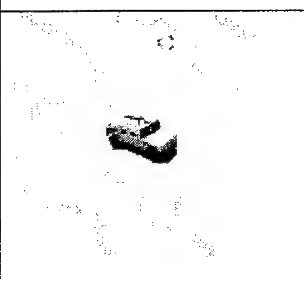
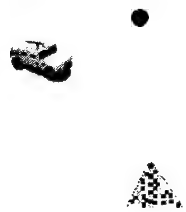
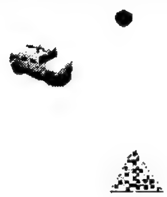
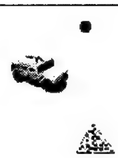
	Input Image	Output of Image Recognition Program	Aimpoint
Frame 10			
Frame 13			
Frame 14			
Frame 16			
Frame 18			

Figure 5. Simulation with stationary target and moving background clutter

	Input Image	Output of Image Recognition Program
Frame 1		
Frame 3		
Frame 5		
Frame 7		
Frame 9		

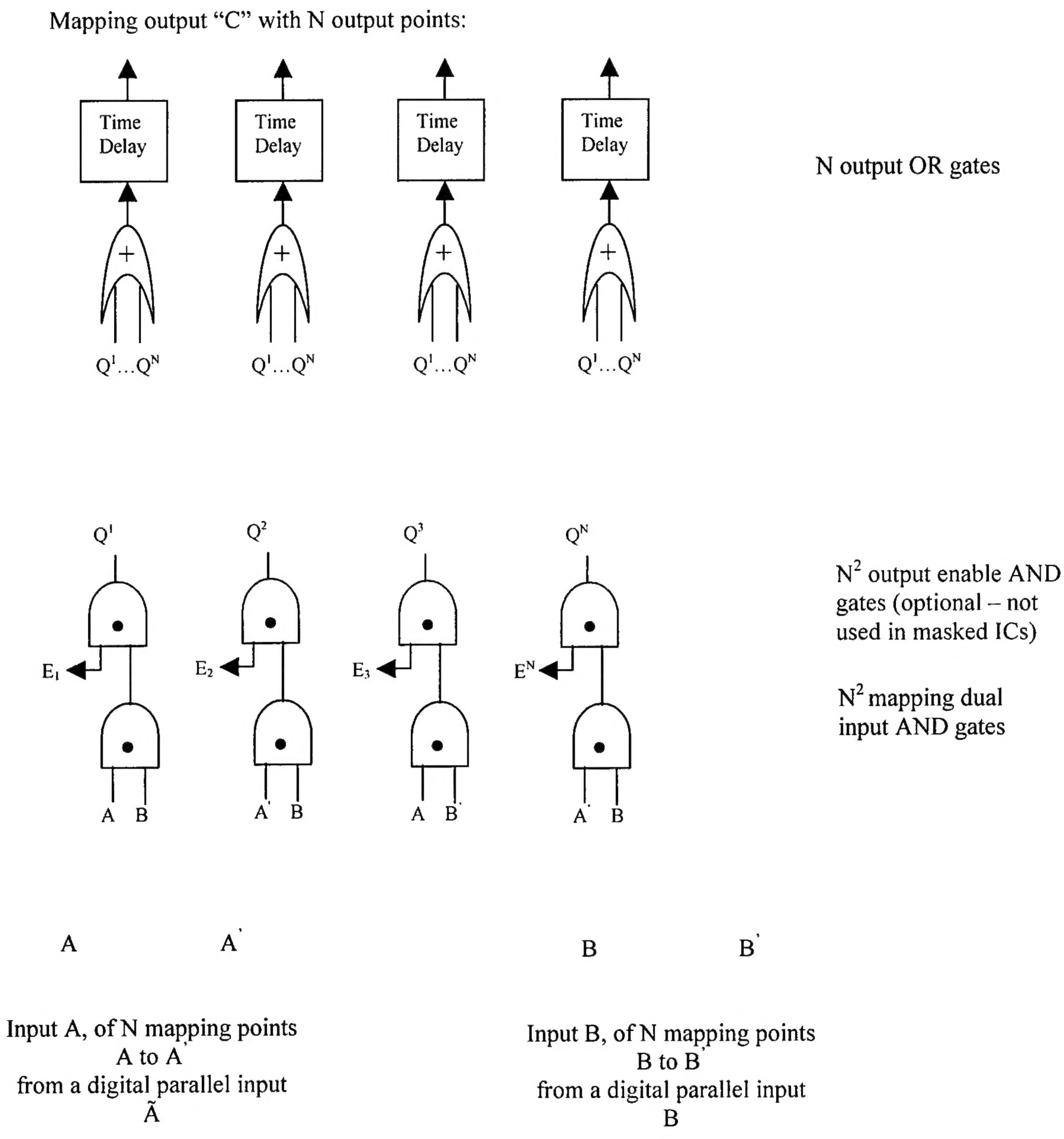
Task 3. Hardware Analysis

Figure 6 illustrates the circuit layout of a basic pattern recognition mapping module using a universal "on the fly" configuration (middle set of "AND" gates). Interfacing mapping modules to a CCD array or to each other requires a method to handle the large numbers of input/output mapping points. For optimum performance, subcomponents (CCD, mapping modules, and mapping modules to digital output) would need to be incorporated on a single chip using very large scale (VLS) integrated circuit technology. This option provides a lightweight, high performance system, but millions of dollars would be required for chip design and fabrication. This option is not viable under the SBIR program.

A more cost effective option would incorporate a set of mapping modules on a single chip with integral parallel type input/output ports. This approach allows the pattern recognition system to be directly incorporated into existing systems at reduced cost and delay. QEI's initial estimate for prototype production of this system is $250,000. Since several iterations of silicon design, fabrication, and testing are anticipated for successful system development, this option is also not viable for a Phase II project.

A viable option for a Phase II prototype system would use embedded algorithms on a microprocessor. This is a cost effective approach that emulates the functionality of the pattern recognition, although it sacrifices the speed and compactness of operation that would be achieved by a true integrated circuit implementation. The Phase II system would not be suitable for field use because of size and memory constraints.

Figure 6. Circuit layout of a basic pattern recognition mapping module using universal "on the fly" configuration



Task 4. Technical and Economic Evaluation

If successful, this technology could have widespread military and commercial applications. In addition to employing the technology on cruise missiles, it could also be used on missile interceptors, air-to-air missiles, and cannon projectiles. Commercially, the technology is applicable to a wide variety of visual control systems including manufacturing process control, aids for the blind, vehicle collision avoidance sensors, autonomous vehicle control, and surveillance systems. The technology would be particularly useful in the control of non-linear, time-varying processes such as non-linear chemical processes and unstable control systems. The proposed control system would be applicable to anything that requires complex pattern recognition in a short time frame or to systems handling long-term drift that require quick response times.

The simulation results indicate that the system adequately tracks a moving target against a stationary background with moving decoys, or a stationary target and decoys against a background that, as a whole, varies over time. Non-target decoy images must contain less than 50% of the target information; otherwise, these images may be identified as targets. This limitation means the system would probably not be able to distinguish between similar target and non-target objects, such as buildings or vehicles. Significant improvements to the image recognition capabilities of this system are needed before it would be useful to either the military or commercial markets.

Cost is another issue. Initially, QEI had hoped that the proposed control system would be easily implemented through combining a digital image sensor, Erasable Programmable Read-Only Memory (EPROM) chips, First-In First-Out (FIFO) buffers, and Field Programmable Gate Array (FPGA) chips. Unfortunately, implementation is likely to prove far more complex. As described in the previous section, optimum performance would require combining all subcomponents on a single chip using VLS integrated circuit technology. Even with significant contributions from a private-sector partner, this option may not be economically viable.

Conclusions

All of the technical objectives for this project have been successfully completed, as follows:

- The imaging seeker data output, control matrices, and output matrices including semiconductor component delay times were mathematically modeled
- The control system response to a variety of input conditions, including rapidly changing scenarios and targets in clutter, was tested
- A preliminary evaluation of materials needed for producing a hardware implementation of this control system was completed

Several simulations of the control system were completed, demonstrating that the system can quickly recognize targets under certain conditions. Currently, non-target images must contain less than 50% of the target information; otherwise, these images may be identified as targets. This is a significant limitation that must be addressed before the control system could be effectively used for military or commercial applications.

The most likely area for improvement is the way target images are embedded in the system and compared to input images. Several options are being considered, although at this time none of the options have been developed to the point that they are ready to be tested.

If these technical issues can be adequately addressed, the control system would have widespread military and commercial applications. For optimum performance, all subcomponents could be incorporated on a single chip using very large scale (VLS) integrated circuit technology. This option, while expensive, yields an extremely fast, lightweight, and performance control system.

References

Sullivan, Gary D. "A Design Methodology for Control Systems Using Symbolic Arrays." Thesis: University of Colorado at Denver, Denver, Colorado, 1999.